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Compact wavelength multiplexer/demultiplexer and method for making the same

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Compact wavelength multiplexer/demultiplexer and method for making th same

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BACKGROUND OF THE INVENTION

Field of the Invention

[0001] The invention is generally related to the area of optical components. In particular, the invention is related to compact wavelength multiplexer/demultiplexer and method for making the same.

The Background of Related Art

[0002] The future communication networks demand ever increasing bandwidths and flexibility to different communication protocols. WDM (Wavelength Division Multiplexing) is one of the key technologies for such optical fiber communication networks. WDM employs multiple wavelengths in a single fiber to transmit in parallel different communication protocols and bit rates. Transmitting several channels in a single optical fiber at different wavelengths can multi-fold expand the transmission capacity of the existing optical transmission systems, and facilitate many functions in optical networking. An international standard wavelength grid has been suggested by ITU (International Telecommunication Union) for the center wavelengths of WDM systems. Different technologies have thus been developed to divide or combine channels or subgroups of channels in the ITU grid.

[0003] From a terminology's viewpoint, a device that multiplexes different wavelength channels or groups of channels into one fiber is a multiplexer, and a device that divides the multiplexed channels or groups of channels into individual

or subgroups of channels is a demultiplexer. Specifically, a multiplexer combines several channels of optical signals into a single signal, or in reverse a demultiplexer separates a single multichannel signal into several individual channel signals, such multiplexer/demultiplexer is referred to a multiplexing/ demultiplexing module, or simply multiplexer or demultiplexer.

[0004] Known devices for multiplexing/ demultiplexing have employed, for example, diffraction gratings, arrayed waveguide gratings and various types of fixed or tunable filters. Gratings typically require complicated alignment systems and have been found to provide poor efficiency and poor stability under changing ambient conditions. Fixed wavelength filters, such as interference coatings, can be made substantially more stable, but transmit only a single wavelength or wavelength band.

[0005] US Pat. No. 5,583,683 to Scobey discloses an optical multiplexing device that spatially disperses collimated light from a fiber optic waveguide into individual wavelength bands, or multiplexes such individual wavelength bands to a common fiber optic waveguide or other destination. An optical block has an optical port for passing multiple wavelength collimated light to be demultiplexed. Multiple ports are arrayed in spaced relation to each other along a multiport surface of the optical block to receive respective the individual wavelength bands. With respective collimators that must be precisely coupled to the multiple ports, the optical multiplexing device can be bulky, expensive and susceptible to varying ambient conditions (e.g. temperature and vibrations).

[0006] Another optical multiplexing device, called compact WDM device, is to mount all WDM filters and collimating means on a common substrate. As shown in FIG. 1, where each of the WDM filters 102-109 and collimators 0-9 can

be tuned separately and fixed to the common substrate. Thus, when a multiplex optical signal including, for example, eight different channels or wavelengths (e.g. $\lambda_1\ \lambda_2\ \lambda_3\ \lambda_4\ \lambda_5\ \lambda_6\ \lambda_7\ \lambda_8$), is coupled to a first collimator (i.e., Collimator 0), the optical signal is coupled to the filter **102** that transmits only λ_1 and the rest is reflected to the filter **103** that transmits λ_2 and reflects the rest. The rest of the signal continues to travel through the rest of the filters **104 -109** and every time the signal hits a filter, a wavelength is filtered out and coupled to a collimator for output.

[0007] However, the compact WDM devices encounter serious problems with assembling tolerance. Analysis and experiment have proved that the assembly error that most sensitively degrades performance of the compact WDM devices is the amplified filter tilting error propagation. This situation can be understood from FIG. 2. If the first filter has a lateral tilt error of $\Delta\theta$, the remaining signal hitting the next filter, or simply the next drop channel λ_2 will experience two errors: the position has a lateral displacement $\sim\Delta\theta\cdot l$, and the incident angle has an error of $\Delta\theta$. As a result, the drop channel λ_2 suffers both in insertion loss and the central wavelength. For the next drop channel λ_3, however, the performance degradation is amplified since the beam reflected from filter tilt is $2\cdot\Delta\theta$ and the position lateral shift is $2\cdot\Delta\theta\cdot l$. As the beam cascading further down, the subsequent drop channel will suffer even more degradation.

[0008] In summary, for the nth drop channel, the incident beam will result in an angular error of $2\cdot\Delta\theta$ angular and a lateral shift error of $(n-1)\cdot\Delta\theta\cdot\ l$. This problem is significant in WDM modules configured for a large number of channels, where a minimal angular tilt of a filter, especially those used in the first few channels, will create amplified beam position deviation, both in lateral position and in angle, resulting in significant insertion loss.

[0009] There thus has been a need for compact WDM modules that minimize the problem of error amplification as discussed above and provide high tolerance for manufacturing with high yield.

SUMMARY OF THE INVENTION

[0010] This section is for the purpose of summarizing some aspects of the present invention and to briefly introduce some preferred embodiments. Simplifications or omissions in this section as well as in the abstract may be made to avoid obscuring the purpose of this section and the abstract. Such simplifications or omissions are not intended to limit the scope of the present invention.

[0011] In general, the present invention pertains to improved designs of multiplexing/ demultiplexing modules. According to one aspect of the present invention, at least a concave mirror is used to compensate the filter tilting errors. For a multiplexing/ demultiplexing module configured for N channels, when the number of concave mirrors is less than N, each of the concave mirrors is placed where an incident traveling distance of a light beam is substantially similar or equal to the reflected traveling distance of the light beam. In other words, at least one concave mirror is provided to compensate the filter tilting errors. When the number of concave mirrors is N, each of the concave mirrors is placed to compensate the filter tilting errors, resulting in a multiplexing/ demultiplexing module with no filter tilting errors at all. Depending on the implementation and a specific requirement for a multiplexing/ demultiplexing module, a concave mirror may be made in accordance with a sphere or an oblate spheroid. Significantly different from the prior art modules or devices, the multiplexing/ demultiplexing modules by the present invention possess no or minimized filter tilting errors.

[0012] According to one embodiment, the present invention is a multiplexing/ demultiplexing module comprising at least a concave mirror placed in such way that an incident traveling distance of a light beam to the concave mirror is equal or substantially similar to a reflective traveling distance of the light beam from the concave mirror, wherein any titling errors carried in the light beam are compensated by the light beam going to and reflecting from the concave mirror.

[0013] According to another one embodiment, the present invention is a multiplexing/ demultiplexing module comprising at least N optical filters, each specified for one of the N channels and transmitting an in-band signal and reflecting all out-band signals; and N concave mirrors, each placed in front of one of the N optical filters to receive the out-band signals for correcting titling errors carried in the out-band signals as a result of the one of the N optical filters being titled.

[0014] According to still another embodiment, the present invention is a method for making a multiplexing/ demultiplexing module configured N channels, the method comprising providing at least a concave mirror; and placing the concave mirror in such way that an incident traveling distance of a light beam to the concave mirror is equal or substantially similar to a reflective traveling distance of the light beam from the concave mirror, wherein any titling errors carried in the light beam are compensated by the light beam going to and reflecting from the concave mirror.

[0015] One of objects, features, and advantages of in the present invention is to provide multiplexing/ demultiplexing module with no or minimized filter tilting errors.

[0010] Other objects, features, and advantages of the present invention will become apparent upon examining the following detailed description of an embodiment thereof, taken in conjunction with the attached drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] These and other features, aspects, and advantages of the present invention will become better understood with regard to the following description, appended claims, and accompanying drawings where:

[0012] FIG. 1 (prior art) shows a compact WDM device;

[0013] FIG. 2 illustrates an angular error and a lateral shift error as a result of the filter being tilted;

[0014] FIG. 3 shows a multiplexing/ demultiplexing module with a concave mirror according to one embodiment of the present invention;

[0015] FIG. 4A illustrates an example of an concave mirror shaped in a portion of an oblate spheroid, where a complete ellipse is shown to facilitate the understanding of the mirror;

[0016] FIG. 4B shows an ellipse (i.e. a projected view of an concave mirror) receiving an incident light beam from one of the two foci thereof and reflecting the incident light beam via another one of the two foci thereof;

[0017] FIG. 5 shows a comparison between a conventional compact WDM demultiplexer and an embodiment of the present invention using a single oblate spheroid mirror;

[0018] FIG. 6 shows a comparison between a conventional compact WDM demultiplexer and an embodiment of the present invention using a single spherical mirror;

[0019] FIG. 7 shows a multiplexing/ demultiplexing module according to one embodiment of the present invention employing an array of concave mirrors; and

[0020] FIG. 8 shows a comparison between a conventional compact WDM demultiplexer and an embodiment of the present invention using an array of concave mirrors.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

[0021] The present invention pertains to new designs of multiplexing/ demultiplexing modules. Traditional modules require precise alignment of optical filters, resulting in high costs, or possess filter tilting errors that incur high insertion losses. According to one aspect of the present invention, at least a concave mirror is used to compensate the filter tilting errors. For a multiplexing/ demultiplexing module configured for N channels (e.g., N=8), when the number of concave mirrors is less than N, each of the concave mirrors is placed where an incident optical distance is substantially similar or equal to the reflected optical distance. In other words, at least one concave mirror is provided to compensate the filter tilting errors. When the number of concave mirrors is N, each of the concave mirrors is placed to compensate the filter tilting errors, resulting in a multiplexing/ demultiplexing module with no filter tilting errors at all. Significantly

different from the prior art modules or devices, the multiplexing/ demultiplexing modules by the present invention possess no or minimized filter tilting errors.

[0022] The detailed description of the present invention is presented largely in terms of procedures, steps, logic blocks, processing, or other symbolic representations that directly or indirectly resemble the operations of optical devices or systems that can be used in optical networks. These descriptions and representations are typically used by those skilled in the art to most effectively convey the substance of their work to others skilled in the art.

[0023] Reference herein to "one embodiment" or "an embodiment" means that a particular feature, structure, or characteristic described in connection with the embodiment can be included in at least one embodiment of the invention. The appearances of the phrase "in one embodiment" in various places in the specification are not necessarily all referring to the same embodiment, nor are separate or alternative embodiments mutually exclusive of other embodiments.

[0024] Referring now to the drawings, in which like numerals refer to like parts throughout the several views. FIG. 3 illustrates a multiplexing/ demultiplexing module **300** according to one embodiment of the present invention. To facilitate the description of the present invention, a top view of the module **300** is shown and it is assumed that the module **300** is used for de-multiplexing a multiplexed signal including, for example, eight different channels or wavelengths (e.g. $\lambda_1\ \lambda_2\ \lambda_3\ \lambda_4\ \lambda_5\ \lambda_6\ \lambda_7\ \lambda_8$). It is understood to those skilled in the art that, when the optical paths are reversed, the same module can be used for multiplexing.

[0025] An optical signal **302** is coupled into the module **300** from a collimator **306** through a pigtail fiber **304**. The collimated light from the collimator

306 is split into two beams at a first filter **308**. The filter is configured to transmit only channel (i.e., in-band signal) and reflect others (i.e., out-band channels). One of the two beam at the filter **308** is the in-band signal (e.g., at a wavelength λ_1) transmitted through the filter **308** and subsequently coupled out of the module **300** by a collimator **312**. The second beam is the remaining out-band channels (i.e., all wavelengths except for λ_1) reflected to the next filter **310** for subsequent demultiplexing.

[0026] Essentially, every time the second beam hits a filter, an in-band channel is transmitted through, resulting in a drop of a wavelength from the remaining out-band channels. The beam is reflected from the filter **314**, as this time, the beam includes the remaining wavelengths $\lambda_5 \lambda_6 \lambda_7 \lambda_8$. Apart from the prior art modules, the beam impinges onto, instead of another filter, a concave mirror **316** that reflects the beam to the next filter for further demultiplexing till all remaining wavelengths $\lambda_5 \lambda_6 \lambda_7 \lambda_8$ are respectively coupled out.

[0027] One of the functions provided by the concave mirror **316** is to compensate the tilting error propagation commonly seen in the prior art modules, for example, in FIG. 1. According to one embodiment, the concave mirror **316** is an oblate spheroid, as illustrated in FIG. 4A, with distances *L*1 and *L*2, from its foci to its reflection surface. Distance *L*1 or *L*2 is defined herein as an optical distance equal to the beam traveling distance from, for example, the filter **308** to the concave mirror **316** or from the concave mirror **316** to the last collimator **318**, respectively. The incident angle θ from one of its foci to the spheroid surface equals to the beam incident angle on the filter **318**. More specifically, *L*1 and *L*2 may be referred to an incident traveling distance and a reflective traveling distance of a light beam. In a preferred embodiment, *L*1 and *L*2 are identical. In a case in which it is sometimes difficult (e.g., N is an odd number) to have *L*1 and

L2 identical, the tilting errors can still be reduced when *L1* and *L2* are substantially similar.

[0028] It is well known that an ellipse has the characteristics in which a light beam coming from one of the two foci will be reflected out through another one of the foci as shown in FIG. 4B. In accordance with FIG. 3, FIG. 4B shows an incident light beam **410** representing four cascaded optical paths come from one of the two foci of the ellipse **408** (i.e., a side view of a partial oblate spheroid), the light beam **410** is reflected through another one of the foci as a reflected light beam **412**.

[0029] Specifically, if the first filter **308** results in a lateral tilt error of $\Delta\theta$, the following drop channels $\lambda_2 - \lambda_4$ will experience the two errors as shown in FIG. 2: the position has a lateral displacement $\sim\Delta\theta \cdot l$, and the incident angle has an error of $\Delta\theta$. However, the errors are reduced after the beam is reflected from the concave mirror **316** (e.g., an ellipsoid concave mirror). The errors in channel λ_5 will have a reduced position lateral displacement and reduced angular error, instead of continuing increasing or amplifying the errors, as exhibited in the conventional compact WDM multiplexer. For channel λ_6 the errors are further reduced. For the last channel λ_8, the errors are completely compensated. The performance comparison between a conventional compact WDM demultiplexer and the present invention is shown in FIG. 5.

[0030] According to one embodiment, a spherical concave mirror with a radius of *L1* is used. As a result, in comparison with the oblate spheroid surface, the position and angular error in the last collimator **318** are not completely, but, partially compensated. A detailed calculations on using a spherical mirror with radius *L1*, assuming the collimator output beams having Gaussian profiles, and

using overlap integrals between the common collimator and the add/drop collimators are performed. The results are compared between using previous art and using the present new design and summarized in FIG. 6. Evidently, the effects of the first filter tilting on the latter channels of the cascading add/drop sequence have reduced.

[0031] Referring now to FIG. 7, there shows another multiplexing/ demultiplexing module **700** according to one embodiment of the present invention. The module **700** includes an array of concave mirrors **702**. Given the description above, it can be appreciated that errors are not amplified at all and corrected immediately in a concave mirror. In other words, positional and angular errors generated by any prior filter tilting are completely compensated for all following channels through the oblate spheroid concave mirror array as shown in FIG. 8.

[0024] One of the features in the present invention is to provide at least a concave mirror to compensate the filter tilting errors. For a multiplexing/ demultiplexing module configured for N channels and with tolerable filter tilting errors, the number of concave mirrors can be less than N, where each of the concave mirrors is placed in such way that an incident optical distance is substantially similar to the reflected optical distance. When it is desired for a multiplexing/ demultiplexing module configured for N channels and without any tolerable filter tilting errors, the number of concave mirrors is N and each of the concave mirrors is placed to compensate the filter tilting errors. Depending on the implementation and a specific requirement for a multiplexing/ demultiplexing module, a concave mirror may be made in accordance with a sphere or an oblate spheroid.

[0032] While the present invention has been described with reference to specific embodiments, the description is illustrative of the invention and is not to be construed as limiting the invention. Various modifications to the present invention can be made to the preferred embodiments by those skilled in the art without departing from the true spirit and scope of the invention as defined by the appended claim. Accordingly, the scope of the present invention is defined by the appended claims rather than the forgoing description of embodiments.